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Multi-Disciplinary Design Optimization Using WAVE

Keith Irwin
General Electric Aircraft Engines, Cincinnati, Ohio

June 2000

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Keith Irwin
General Electric Aircraft Engines
Cincinnati, Ohio 45135

Introduction

The current preliminary design tools lack the product performance, quality and cost prediction fidelity required to design Six Sigma products. They are also frequently incompatible with the tools used in detailed design, leading to a great deal of rework and lost or discarded data in the transition from preliminary to detailed design. Thus, enhanced preliminary design tools are needed in order to produce adequate financial returns to the business.

To achieve this goal, GEAE has focused on building the preliminary design system around the same geometric 3D solid model that will be used in detailed design. With this approach, the preliminary designer will no longer convert a flowpath sketch into an engine cross section but rather, automatically create 3D solid geometry for structural integrity, life, weight, cost, complexity, producibility, and maintainability assessments. Likewise, both the preliminary design and the detailed design can benefit from the use of the same preliminary part sizing routines. The design analysis tools will also be integrated with the 3D solid model to eliminate manual transfer of data between programs.

GEAE has aggressively pursued the computerized control of engineering knowledge for many years. Through its study and validation of 3-D CAD programs and processes, GEAE concluded that total system control was not feasible at that time. Prior CAD tools focused exclusively on detail part geometry and Knowledge Based Engineering systems concentrated on rules input and data output. A system was needed to bridge the gap between the two to capture the total system. With the introduction of WAVE Engineering from UGS, the possibilities of an engineering system control device began to formulate. GEAE decided to investigate the new WAVE functionality to accomplish this task. NASA joined GEAE in funding this validation project through Task Order No. 1.

With the validation project complete, the second phase under Task Order No. 2 was established to develop an associative control structure (framework) in the UG WAVE environment enabling multi-disciplinary design of turbine propulsion systems. The capabilities of WAVE were evaluated to assess its use as a rapid optimization and productivity tool. This project also identified future WAVE product enhancements that will make the tool still more beneficial for product development.

GE's Intelligent Master Model Initiative

GE's current preliminary design process is not integrated with the detailed design process. Efforts over the past several years were initiated to resolve this problem. For the seamless transfer of a design, teams were formed consisting of PD and detailed design experts. These teams identified the types of data and the level of analysis that was needed or required by the detailed designer as the design was handed over at program launch. The improved process, shown in Figure 1, is an integral part of the overall product creation process. As shown in the figure, the System Oriented Layout with Integrated Design (SOLID) project is actually the beginning of the Intelligent Master Model (IMM). The figure shows the product design cycle starting at the advent of the initial requirement and extending to engine certification. The IMM's generated by SOLID flow to detailed component design and CAD integrated detailed analysis, to the digital mockup of the engine assembly and all the way to the component manufacturing model. Due to the cohesive assocativity of all disciplines to the IMM, global & detailed changes will be realized throughout the product community.

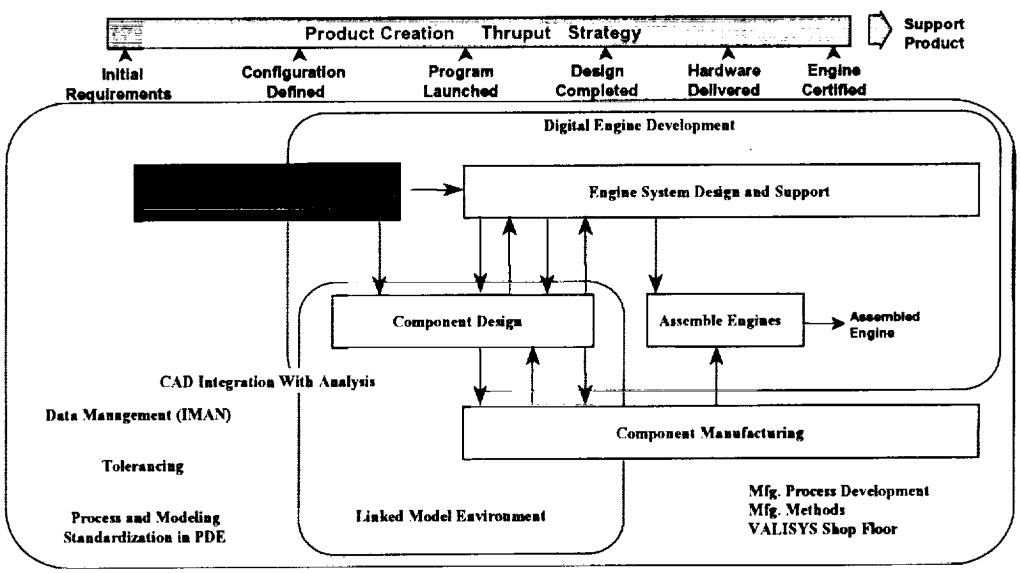

Figure 1: Improved Product Creation Process

SOLID Starts the Design Process/Intelligent Master Model

As Figure 2 illustrates, the designer starts with existing modules and associated 3-D solid engine assembly/Master Models stored in the UG/Iman component library. Once the engine baseline configuration is established, inputs such as the updated thermodynamic cycle data, life requirements, material property initial assumptions and the technology definition defined by IOC are manipulated to modify this configuration. These inputs combined from the outputs from the CPD routine, as well as, other Process Integration (PI) tools then feed the fully associative parametric model from SOLID. The functionality called WAVE within UG then allows part manipulation through geometry changes based on engineering rules, such as bore stress, and size updates based on changes to air mass flow. Since a 3-D CAD model of the engine configuration is associated to both the system level and the design requirements, the designer will be able to obtain higher fidelity weights and CG and perform higher fidelity analysis. As the design matures through part optimization, the Master Models will be able to update and morph quickly due to the associativity between modules and subsystems.

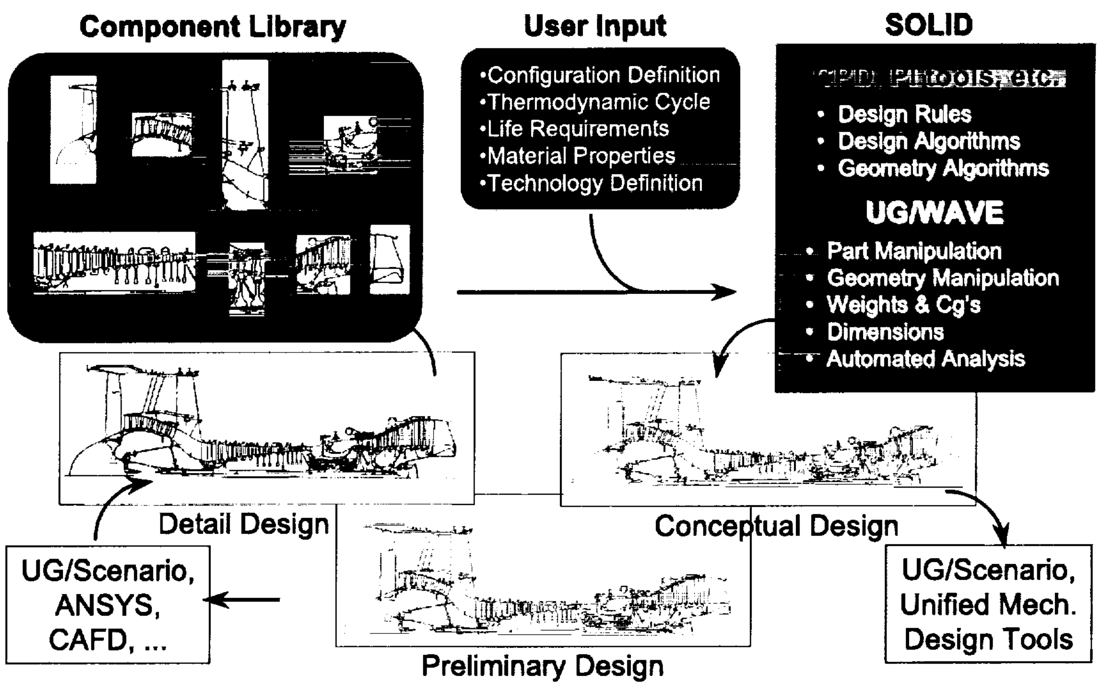

Figure 2: Manipulation of Geometry Using WAVE

WAVE Functionality within UGS Makes it All Possible

CAD systems have had the ability to capture detail information of single parts in an assembly for many years but, control over the entire design system that maintains associativity between system level non-geometric inputs and rules, and part geometry has been elusive. WAVE engineering gives design engineers a unique system control device for the capture and association of the design requirements and specific rules with CAD geometry. With any systematic approach to design, the design process of a system needs to be understood.

A quick study of design systems reveals a structure to the dissemination and control of data (Figure 3). The customer has requirements that need to be met from the large system level; the layout of the system level is fixed to those requirements; the layout imposes the design structure on the module subsystem level; the module subsystem level imposes its layout on the sub-systems; the sub-systems control the environment for the detail parts; the parts are brought together in a product assembly.

UGS WAVE technology allows the various designers and project leaders to control the sharing of geometry created from their non-geometric rules by developing a typical UG assembly. The dramatic difference between a standard assembly and a WAVE assembly (Product Control Structure) is that the PCS maintains associativity between the systems and subsystems by a nearly unlimited ability to copy geometry from one control structure component to another. This structure therefore allows the design rules in the PCS to flow through copied geometry in a TOP DOWN fashion,

The lowest subsystem in the PCS conveys its geometry to the product assembly by creating a linked part (lowest component file of the engine assembly). The geometry contained in the linked part is used to create 3-D solid objects that represent the final machined part in the product structure. These linked parts are subsequently added as components to subassemblies and finally into the top product assembly using standard UG assemblies and components. Through this process the Master Models (linked parts) are associated to the Large System requirements in the PCS. Any changes in the PCS will result in an update to the 3-D components of the Product Assembly and the associated Analysis, Manufacturing and Drawing context models.

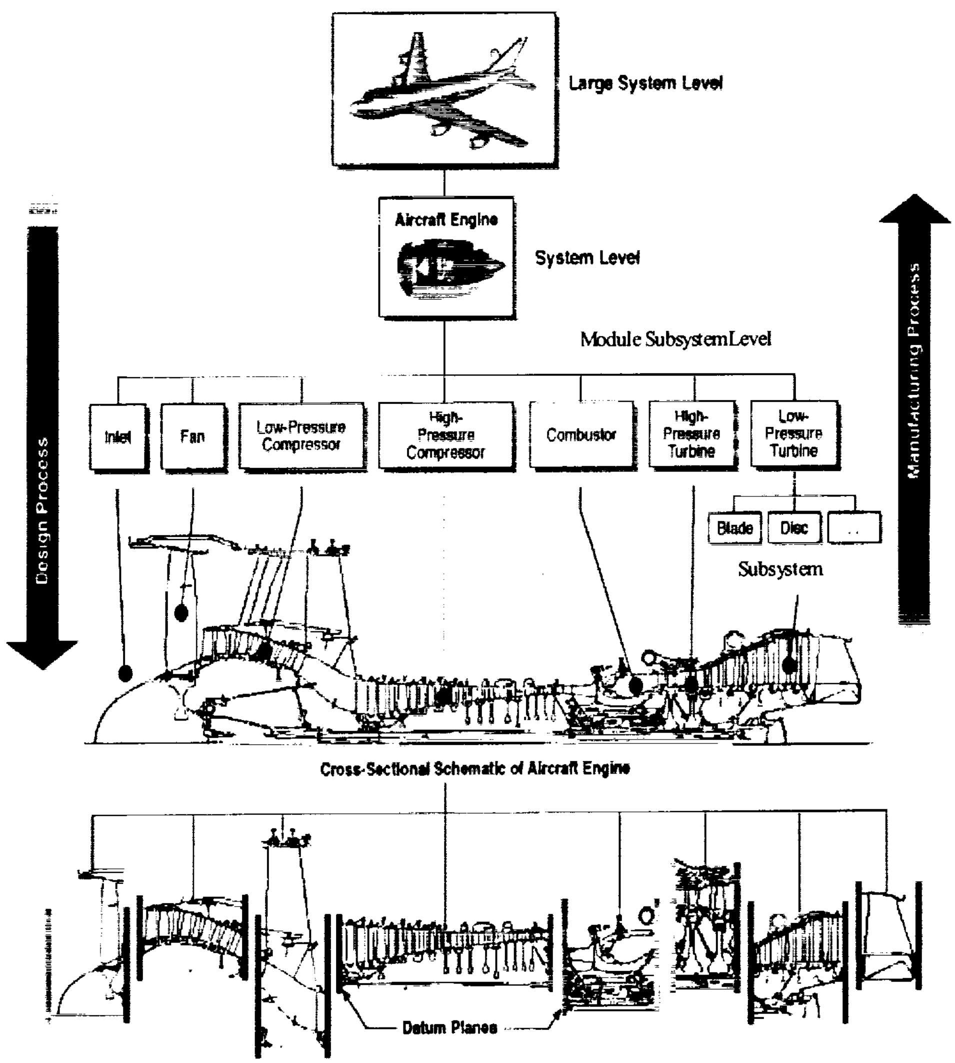

Figure 3: Hierarchy of Control Structure

With the proper adherence to a structured investigation and implementation process a Product Control Structure may allow a company to:

-Electronically capture and record system and sub-system knowledge

-Disperse knowledge to individuals and groups while, at the same time, controlling the data

-Establish the configuration of the system and sub-systems

-Permit multiple system, subsystem and assembly configurations

-Quickly control updates to system & sub-system data connected to solid master model geometry

-Determine where geometric or non-geometric conflicts arise as the changes occur.

-Negotiate the interfaces between sub-systems and parts

-Allow for system, sub-system and assembly reuse for derivative engine design

-Mimic the political structure of a company

Proving UG/WAVE on an Aircraft Engine

In 1998 a pilot project was launched with the objective to prove the functionality of WAVE in the context of a turbofan engine. It was determined that to understand the configuration of an engine system, the large system or vehicle system control must be initially identified. A group of aircraft and engine system engineers was organized and a thorough investigation was conducted identifying the interfaces of the large system, propulsion system, EBU system and nacelle system. This information directly identified the first two levels of the Product Control Structure (PCS). The uppermost level of our structure, called Engine, contains all of the design assumptions, cycle data, module boundaries defined by datum planes, and engine airflow. Just below engine is where the major modules are defined: Fan, Booster, HPC, Combustor, HPT, and LPT. These modules contain data similar to the engine level except for their specific module. Datum planes, datum axes, and points are used at this level to define the module interfaces. The cycle information pertinent to the specific module is copied down from Engine level. The Aero module is also defined at this level and contains information defining the gas path of the engine and the 3-D airfoils. Since this was a validation project, the Module System Levels developed simplified representations of their subsystem components.

With the PCS generated, simple scaling rules were defined for the modules and sub-systems. To demonstrate the associativity of the WAVE functionality, a 10% radial flow scale was ordered at engine level. The impact of the change cascaded down through the entire structure morphing the engine to its new flow size. The parametric, associative model performed this update in less than 30 minutes compared to 2-3 months to generate a new CAD model in the current system.

The flow scale used simple scaling rules since the intent was only to determine if the WAVE functionality worked with the complex PCS of a turbo-fan engine. A second pilot project was initiated to determine if the update would work on a more complex model. A detailed parametric model with design rules driving the parametric sketches was developed for stage 4 of the HPC. Spreadsheets were developed to drive the parametric sketches using engineering rules based on platform thickness requirements, shank stress, crush stress, disk post stress, weak link margin, and other rules driven by manufacturing, producibility, and assembly requirements, as shown in Figure 4. A master model of the disk assembly was generated containing a disk and a foreward spacer arm. A mesh was created of the model and a stress analysis was completed using ANSYS. The 10% flow scale was performed and the model was 're-meshed' and the analysis completed in just minutes by rerunning the log file that was generated during the first analysis. The second pilot project showed that the possibilities for this type of model were endless.

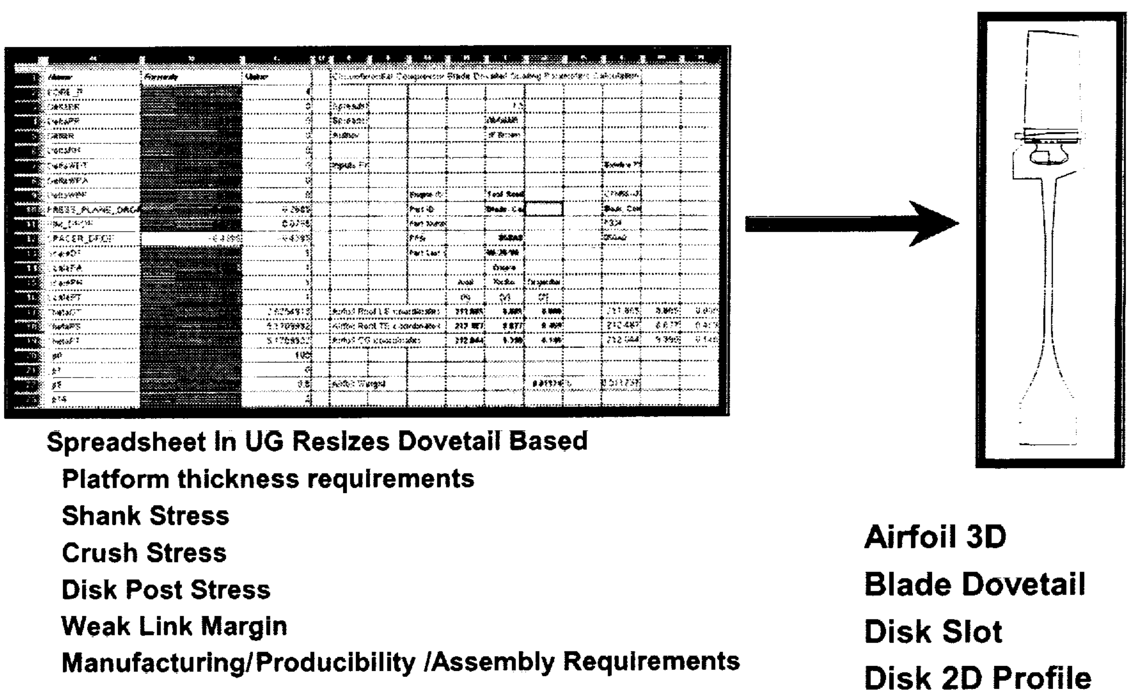

Figure 4: Parametric Sketch Driven from a Spreadsheet

Building the SOLID Model

With WAVE sufficiently validated, the next goal was to use this functionality to generate a full parametric associative model. This model will become the foundation for the IMM. The initial pilot project was demonstrated using UG version 13 beta software. However, to completely develop the SOLID/WAVE model requires the additional functionality that is available in UG V15 software. UG V15 was also required by GE Aircraft Engines to meet our Y2K requirements. The model was converted from V13 to V15 during the first part of 1999. This required importing most of the V13 sketches into the V15 part files and making sure that the structure remained associative during a WAVE update. The final engine assembly is shown in Figure 5.

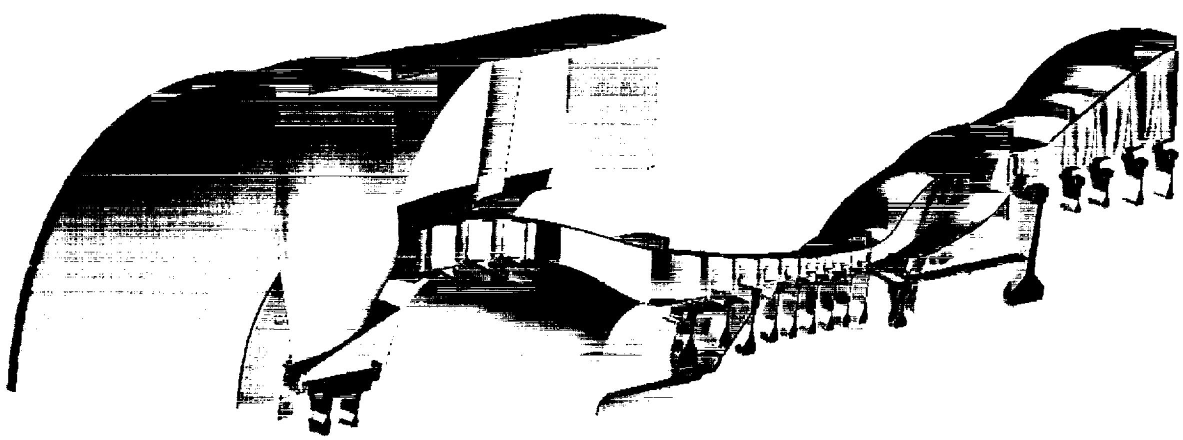

Figure 5: UG-WAVE Derived Engine Assembly

The initial model developed in the pilot project used data from the CPD routine to define the gas path of the engine, the beginning and ending of each model, and other data such as blade counts, rotationary speeds, blade radius ratios, spacing, etc. This method required a manual update of the UG spreadsheets in the Engine and Aero levels. To eliminate the need for this redundant update, a transfer routine was written which modified the CPD code. This enhancement provided the UG part files with the updated parameters from CPD without the aid of UG spreadsheets (Figure 6). Both of the above tasks were completed under NASA Task Order #2.

- CPD exports stage leading and trailing edge coordinates to Excel
- Excel exports coordinate expressions to UG flowpath sketches

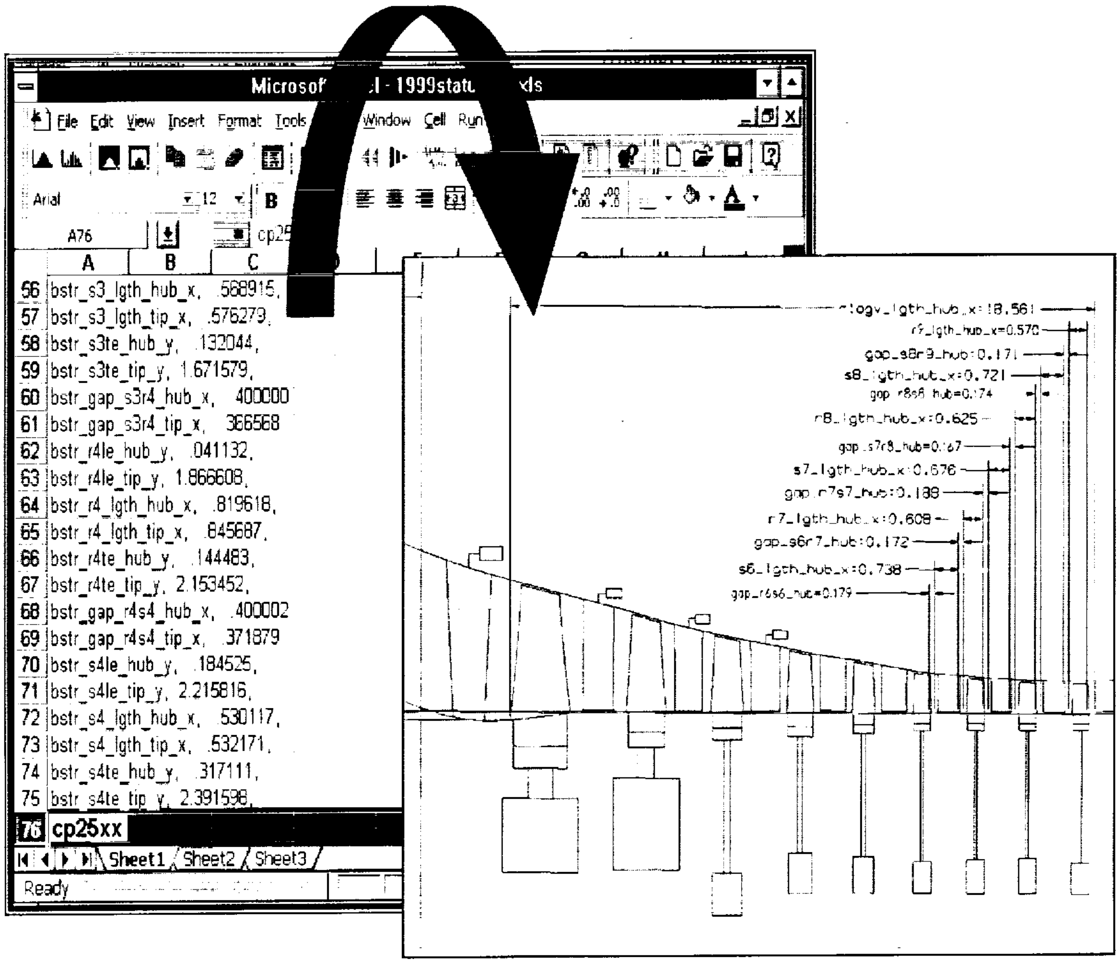

Figure 6: UG Sketch Derived from a Spreadsheet

Core Development

The goal for 1999 was to develop a fully parametric associative model of an engine core (Figure 7). The core was broken into 3 modules; the high-pressure compressor (HPC), the combustor, and the High Pressure Turbine (HPT). Teams were formed for each module with membership consisting of preliminary, advanced, and detailed design groups. The intent was to get the eventual part owners involved in the development of the PCS and the actual design rules. It became clear in this project and for the success of future projects that the content of the PCS must have the confidence of all facets of the design community.

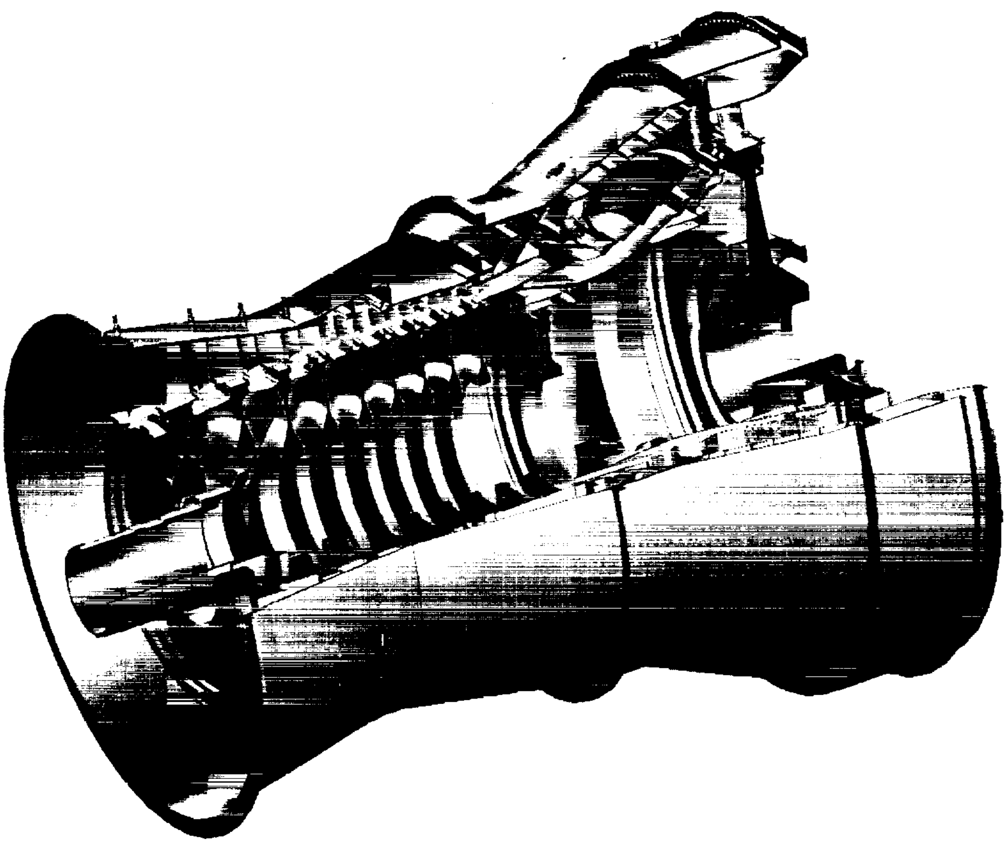

Figure 7: Fully Parametric Associative Model

Module Teams

The first task of the groups was to determine all the interfaces that exist for their particular module, both external and internal to the module in question.
An interface describes the relationship between geometric entities. These relationships can be constructed with any geometry where a parent-child association can be established, for example:

1) A datum plane, surface or series of curves can describe the mating surface of two or more parts
2) A datum plane, surface or series of curves constructed at a specified distance from another datum plane, surface or series of curves defines a gap between two or more parts
3) A datum axis or line can be used to define the engine centerline or bolt hole center
4) A point determines a 2-D reference location for other geometry or parts

Interfaces are classified as either internal or external.

1. An internal interface is defined and controlled by one module and referenced only in that module.
2. An external interface describes relationships between modules.

External interfaces are further classified into the following 3 levels:

Level 1: An interface defined and controlled by one upper level module and imposed on other lower level modules.

Level 2: An interface between two modules that neither module directly controls – the control structure interface is located one level above the modules.

Level 3: An interface between two modules that one module directly controls – the control structure interface is located in that module.

Meetings were conducted to determine what was imposed on the designer, why was the sub-system there, what was its function, and why did it look the way it did. Debate was usually involved and multiple iterations through the module were required before all of the necessary data was gathered. It was essential to understand the design intent of the subsystems for the model to update correctly when a design change is implemented.

Blade Methods

Early in the project it became obvious that the airfoils had to be 3-D solids since airfoils complex geometry can't be described using simplistic sketches due to their complex geometry. However, getting accurate airfoil weight and CG is vital to generate accurate disk and case designs. This exposed a number of problems.

1. How do we get an accurate representation of the 3-D airfoil early in the PD environment?
2. What rules do we use to morph or scale these 3-D airfoils?
3. How is this done in the CAD environment?

The initial pilot project used airfoil blades developed in the CPD routine, which are constructed using circular arc airfoil sections. In order to get actual blade representations in the model two projects were started. One for the HPC and one for the HPT, with the objective to generate transfer functions to scale the 3-D data sets using 1-D aerodynamic analysis. Work was also initiated to solve the problem of getting the new data into UG and morphing the airfoils. A subroutine is being written which will automatically run the transfer functions using updated 1-D analysis and morph the existing airfoils within the UG framework. This routine is in its final stages and should be available early in the year 2000. Figure 8 illustrates the operations this routine will perform.

3-D Airfoil Creation

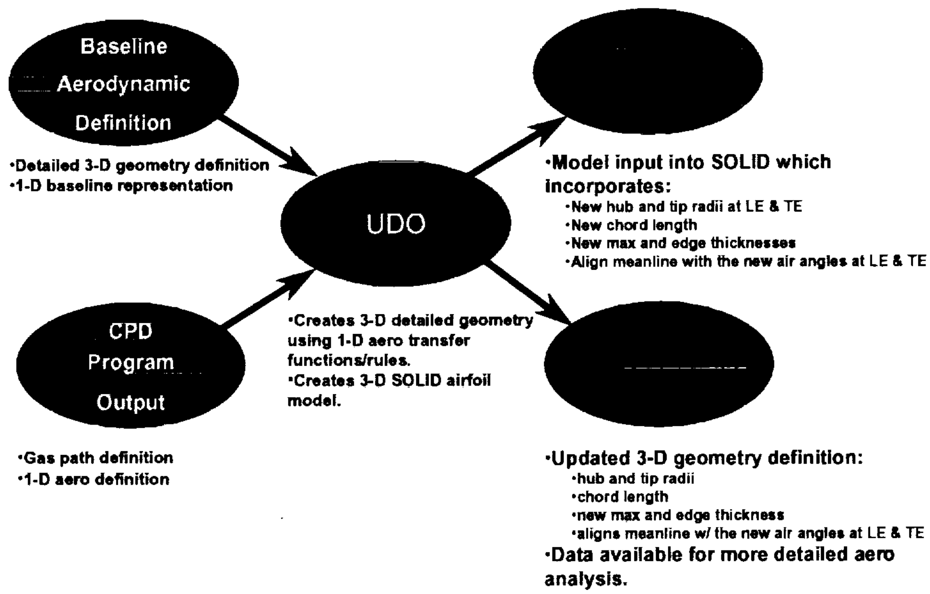

Figure 8: User Defined Object Routine

Knowledge Based Engineering (KBE)

Throughout the 80's and 90's a number of initiatives took place within GE and the engineering community at large to provide a method of embedding the "why" and "how" of a design into the "what" of the design. Initiatives such as Artificial Intelligence, Rules Based Design and KBE have all been used to attach the knowledge of how a design would change when subjected to changing requirements and constraints. Rather than defining the static design of a part, the rules used to manipulate the design are incorporated into the design itself thereby embedding design knowledge into the part.

A number of commercial KBE codes have been available over the years such as AML by Technosoft, Design++ by Design Power, ICAD by KTI and Intent by Heide Corp. Typically these codes have been used to build a design model with embedded rules of a given part or sub-system. Integration with CAD codes such as Unigraphics has been limited and full system designs have not been the norm but the exception. Our objective on the SOLID project has been to create an engine design system which fully incorporates Knowledge Based Engineering technology into a top-down system design with tight integration into the GEAE CAD code Unigraphics. It is the top-down approach and the tight integration with CAD which makes this program unique. Figure 9 shows the differences between a classic KBE system and the KBE methodology applied to the SOLID program.

Recent developments outside of GE have helped the development of the SOLID goals. On August 9th 1999, Unigraphics Solutions and Heide Corp announced a partnership which included, among other things, the embedding of the Heide Corp KBE code Intent into the Unigraphics CAD package. This development advances the goals of the SOLID project by providing a method for rules to be associated with system, sub-system and part designs as an integral part of the CAD system. Currently, Unigraphics has the capability to define associativity among geometric features of components of an assembly (UG/WAVE) but this new product (UG/KBE - a merger of UG and Intent) will additionally provide parameter and rule associativity.

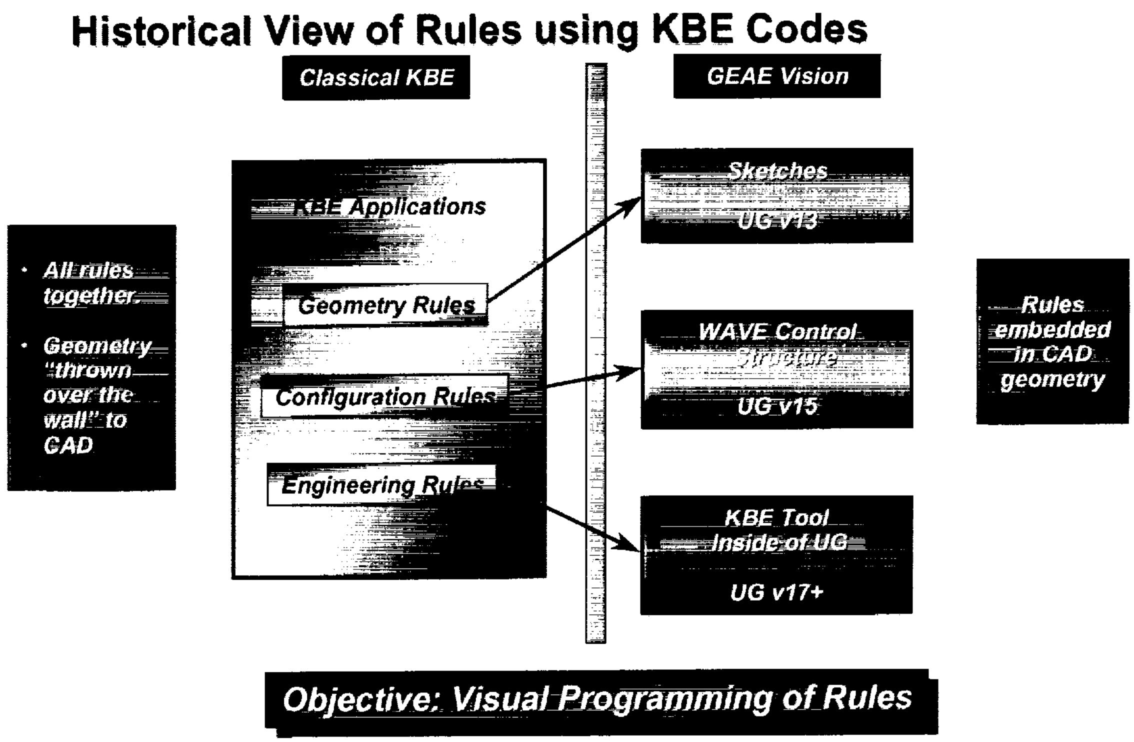

Figure 9: Classical KBE vs. GEAE Vision

Activities currently scheduled for 2000

The focus of Task Order 2 was to build an associative control structure for an engine HP system, or core, to produce linked engine geometry that flows seamlessly to the detailed design and responds to high level requirement changes. This model was built using design rules provided by GEAE to drive the linked geometry. The scope for the next year of the project is to build an LP system model using design rules and algorithms to drive detailed geometry. As Phase 2 progressed, it became increasingly apparent that in order for this system to become a true production design system it will require the addition of Process Integration (linkage to codes such as APNASA) and KBE. This is due to the fact that a number of rules are needed to drive geometric changes, as well as, the realization of greater potential that this system can deliver.

The efforts for next year will utilize the work completed during the previous phases and start development of a productivity tool to enable multi-disciplinary design of an LP propulsion system. Work will focus, but not be limited to the following areas:

1. Continued development of the control structure incorporating Air Vehicle interfaces and module/part interfaces that were not part of the initial task order.
2. Creation of generic Sketches to populate the control structure.
3. Incorporation of additional features from Computerized Propulsion Design (CPD) to drive geometric changes.
4. Development of Process Integration (PI) methodology to link geometry with design, analysis and optimization.
5. Utilize KBE to drive UG geometry from a rules database.
6. In partnership with Unigraphics Solution, develop a reporting system for part lists, materials, weights, and costs.
7. Integration with NCP to support the flow of information/data.
8. User Interface development in conjunction with the NCP Interface design.
9. Integration of a cost model in order to produce detailed costs that are being driven from higher fidelity parts.

Summary

GEAE has long realized that its product development process required enhancements to better meet the needs of its customers. One long-term vision was to develop a new process that allowed the preliminary design data to be seamlessly transferred to and developed further by detailed design. The ability to organize, control and update the upper level engine parameters that subsequently drive the design of detail engine parts was also a requirement of the new process. The System Oriented Layout with Integrated Design (SOLID) project was conceived to investigate the development of this new product development process.

In the past, industry tools were not capable of developing the complete engine system that GEAE required. In 1997 Unigraphics Solutions introduced functionality called WAVE Engineering that could deliver the desired control and associativity of 3D CAD data. The WAVE functionality allows the creation of a Product Control Structure with top-down control. The PCS is organized so that system level criteria drive the subsystem level criteria, located in the lowest level of the PCS. Likewise, the files that represent the actual engine parts are linked to the subsystem level criteria. Thus, a change to the system level criteria will cascade down and modify the engine part 3D CAD data.

To begin the investigation of this new technology GEAE teamed with NASA to form the Task Order No.1 project. The first aspect of this project was to investigate the requirements of a turbofan engine system and develop a PCS. Once the PCS and associative engine parts were created, it was demonstrated that a 10% radial flow scale at the system level would appropriately update the engine parts. Having successfully demonstrated the capabilities of WAVE on a simplified engine system, a second pilot under this project was developed to determine how a complex system would perform. Additional detail and intelligence was added to the existing stage 4 disk files and an associative analysis file was created. Again, a 10% radial flow scale at the system level correctly updated the entire engine system.

With the objectives of Task Order No.1 successfully completed, GEAE was ready to develop a complete associative engine system using WAVE technology. NASA Task Order No.2 was formed to convert the UG V13 data created under Task Order No.1 to UG V15. Another accomplishment of this project was to improve how CPD data is delivered to the engine system.

The main focus of 1999 was to build upon the engine system data that was delivered under NASA Task Order No.2. The existing PCS and associative engine parts represented simplified versions of the interfaces and rules required to develop a fully parametric associative model of an engine core. Module teams consisting of preliminary, advanced and detailed design engineers were formed to obtain the required information and controlling rules to accurately drive the engine core system. Each module was updated to include the intelligence gathered during these investigations.

The future direction of the SOLID program will focus on implementing enhancements and creating the structure to define the fan, booster and low pressure turbine modules. The ability to morph the engine airfoils and manipulate design rules with new UG KBE functionality will dramatically enhance GEAE's capability to manage the top-down design of a complex engineering system, such as an entire turbofan engine.

Appendix

Terms	Description
1D	One Dimensional
3D	Three Dimensional
AML™	Knowledge-based Engineering software developed by Technosoft
ANSYS™	Computer Aided Engineering software developed by ANSYS Inc.
APNASA™	NASA 3D Multi-Stage Computational Fluid Dynamics Solver
CAD	Computer Aided Design
CAFD™	Circumferentially Averaged Flow Determination (GE Axi-Symmetric Computational Fluid Dynamics Solver)
CG	Center of gravity
CPD™	Computerized Propulsion Design (GEAE) flow path design code
Design++™	Knowledge-based Engineering software developed by Design Power
EBU	Engine Build Up
GE	General Electric Co.
GEAE	General Electric Aircraft Engines
HPC	High Pressure Compressor
HPT	High Pressure Turbine
ICAD™	Knowledge-based Engineering software developed by KTI
iMAN™	Product Data Management System developed by Unigraphics Solutions Inc.
IMM	Intelligent Master Model
Intent!™	Knowledge-based Engineering software developed by Heide Corp.
IOC	Introduction of Concept
KTI	Knowledge Technologies International
KBE	Knowledge Based Engineering
LE	Leading Edge
LP	Low Pressure
LPT	Low Pressure Turbine
NASA	National Aeronautics & Space Administration
NCP	National Cycle Program
PCS	Product Control Structure
PD	Preliminary Design
PI	Process Integration
SOLID	System Oriented Layout with Integrated Design (GEAE)
TE	Trailing Edge
UDO	User Defined Object
UG™	Unigraphics – Computer Aided Design, Manufacturing & Engineering software developed by Unigraphics Solutions Inc.
UGS	Unigraphics Solutions Inc.
UG/Scenario™	Computer Aided Engineering software developed by Unigraphics Solutions Inc.
WAVE™	System engineering software developed by Unigraphics Solutions Inc.

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Keith Irwin

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General Electric Aircraft Engines
One Neumann Way
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13. ABSTRACT *(Maximum 200 words)*

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